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INVESTIGATING THE INITIAL PHASE OF A DISCHARGE WHEN INTERELECTRODE GAPS ARE VERY SMALL

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/Figures referred to are appended./

Previous research carried out in the Power Engineering Institute imeni G. M. Krzhizhanovskiy of the Academy of Sciences USSR (1) has indicated that for the circuit shown in Figure 1, the variation of voltage U_1 across a spark gap in air takes the form shown in Figure 2a and more fully in Figure 2b.

It was found that the U_1 variation curve normally conformed to Type A, and that discharges in which U_1 dropped more rapidly, as in Type B, were only observed in a few cases.

Multiple oscillograms showed that when C varies from .0025 to 14.5 mfd in a voltage range from $U_0 \approx 1$ kv to 5-20 kv, where R consists only of the spark resistance and L varies from $5 \cdot 10^{-8}$ to $1.3 \cdot 10^{-6}$ h, the path of the Type A curve is scarcely altered. The period τ_1, from the beginning of the voltage drop at the spark gap to the moment of its retardation, varies from $0.4 \cdot 10^{-8}$ to $1.5 \cdot 10^{-8}$ sec. A slower drop of U_1 to an almost steady value occurs in the period τ_2 which varies from 1.2 to $9.5 \cdot 10^{-8}$ sec. In experiments described in this article the size of the spark gap δ varied from 0.3 to 7 mm and the air pressure p in the interelectrode gap varied from 1 atm to 2-2.5 atm. The minimum value of the product of $p\delta$ was $760 \cdot 0.03 = 22.8$ mm (mercury column) $\times$ cm, and the maximum value was $760 \cdot 2.5 \cdot 0.7 = 1330$ mm (mercury column) $\times$ cm.

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In recent years, a spark-over in the gaps where $p\delta > 200$ has been treated as a single-flow electron process. The brevity of the initial stage of spark discharge is explained by the very rapid development of a flow of electrons from the cathode to the anode. Where $p\delta$ is less than 200, the discharge cycle conforms with Townsend's Theory, but although the form of this theory is preserved when the size of the spark gap δ is reduced to very small values of the order of $10^{-2} - 10^{-3}$ mm, processes at the electrodes become the dominating factor.

With regard to these processes at the electrodes, until recently, the discharge mechanism had not been studied in sufficient detail for cases where $p\delta = 0.5$-5, although at the present time discharges across very small gaps where $\delta = 100 - 10$ microns are of great practical importance. This applies particularly to the electric-spark machining of metals which is normally carried out at voltages of 300-250 v and less. An understanding of the processes occurring in the initial stage of a discharge is necessary when studying the discharge mechanism taking place in the plasma and at the electrodes, but despite considerable research effort in this respect, no solution had been reached until recently.

During 1949, the Power Engineering Institute of the Academy of Sciences USSR and the Ministry of Machine Tool Building USSR carried out research on the electrical processes occurring during the electric spark machining of metals, including the initial stage of discharge. Prolonged experimentation led to the conclusion that in the case of a discharge where the interelectrode gap δ is extremely small, the voltage variation curve of U_1 becomes a smooth curve when $U_0 < 250$-300 and avoids the rapid voltage drop from U_0 to U_{SH_1} shown in Figure 2.

It is reasonable to assume that in the case of very small interelectrode gaps ($\delta < 10$ microns) where the electrode surface have been subjected to the action of previous discharges, it is most likely that contact bridges have been, or will be, quickly formed in various parts of the interelectrode gaps. In this case, the voltage variation of U_1 would be affected by the burning of these current-carrying bridges, and even if they did not exist previous to the beginning of the voltage build-up at the gap, the enormous field gradients (500-1,000 kv per cm) developing in the gap would lead to the escape of ions from the electrode surfaces. This would tend to promote, but not necessarily cause, the disintegration of the anode by bombardment with electrons originating at the cathode and in the gap, if the latter is greater than the mean free path of an electron in a given medium. This occurrence would be confirmed by the positive transfer of metal from the anode which we call "fine transfer" /tonkiy perenos/. Until recently, however, interelectrode bridges had not been observed and the way in which they developed remained in some doubt (2).

The formation of interelectrode bridges is, of course, facilitated by the presence, on the electrode surfaces, of small projections commensurate with the interelectrode gap, and in the case of a liquid medium by the presence of dirt in the form of metallic dust (for example, erosion products of electrode material) or of carbon black and other pyrolysis products of liquid hydrocarbons. The experiments described below were carried out in the Power Engineering Institute of the Academy of Sciences USSR with the object of further clarifying the effect of the presence of dirt in the spark-cutting gap on the initial stage of a discharge.

Studying the Path of the Curve of U_1 Where Artificial Bridges are Formed

Experiments were carried out on the artificial formation of bridges, and the establishment of conditions facilitating their development, in order to clarify the effect of bridges on the voltage curve at the electrodes. (A. Ye. Artamonova collaborated in the experiments described below.)

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The circuit shown in Figure 3 enables recordings to be made of the initial stage of a discharge from a very rapidly charged capacitor C_1. In this circuit, a capacitor C_0, charging from a rectifier unit, is connected to a capacitor C_1 through a resistance R_0 from a light relay M. The operation of the circuit begins when the spark-over of the gap S_a in the timing circuit excites the gap S_v. The voltage across S_1 appears to start above zero due to the delayed sweep of the oscillograph.

The apparatus used in measuring the resistance R_i of the bridge consists of a galvanometer G connected through a 22-v dry battery and a resistance R_2 equal to 10,000 ohms; the measuring circuit is connected to the terminals of the gap S_1. The size of the resistance R_i can be obtained from the galvanometer readings, allowing of course, for the parallel resistance R_1. The resistance R_i is in fact a bridge formed in the interelectrode gap.

The discharge circuit was analyzed analytically to establish the effect of the resistance R_1 on the behavior of the voltage curve $U_i(t)$; Figure 4 shows the results for a number of different cases. It should be noted that over a time interval of 1 μ sec, the path of the curve $U_i(t)$ remains almost unchanged when R_i is reduced from 10,000 ohms to 8-10 ohms, and that U_i is only noticeably reduced for the smallest values of R_i. It follows from this that when using the circuit described above, which is very sensitive to the presence of resistance R_i by virtue of the small size of the capacitor C_1, it would be difficult to detect, by any change in the voltage $U_i(t)$, a bridge, whose resistance R_i exceeded 10 ohms.

Oscillographs were then taken for different values of R_i, which was varied by connecting permanent resistances into the circuit while keeping the remaining factors at a constant value. These oscillographs showed that the calculated and recorded changes of $U_i(t)$ agreed.

Spark Gap in Air

The creation of artificial bridges was achieved by depositing a dry steel powder on the electrodes, using an interelectrode gap δ of 0.1-0.2 mm. The resistance R_i of the bridge was determined in the manner described above. It was found that the size of R_i varied within very broad limits from 5-10 ohms to hundreds of thousands of ohms. At first, investigation of the effect of the bridges on the variation of $U_i(t)$ was made visually on the screen of a cathode-ray tube, and after hundreds of recordings had been made, changes in U_i with time were photographed on a film.

The following method of studying the effect of bridges was then used:

In the first series of experiments, voltage variations of $U_i(t)$ were studied during spark-overs across dry electrode surfaces using an initial capacitor voltage U_0 of 400 - 850 v. Figure 5a shows a typical oscillogram for the first series of recordings taken during the discharge of a capacitance equal to 30 mfd, using various initial voltages. It can be seen that the voltage drops very sharply at point a_1 without any previously noticeable variation. Where the initial voltage U_0 is unaltered, the character of the variation of $U_i(t)$ remains practically constant until the drop begins to slow down at point b_1. The slowed-down part of the variation of U_i in the initial stage differs somewhat for different discharges, due, evidently, to surface effects at the electrodes. The time interval Δt of the drop in U_i should therefore be taken between the values of U_0 and $U_0/2$ in Figure 13, for which Δt is equal to $2.4 \cdot 10^{-8}$ sec.

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Figure 5b shows oscillogram No 126, taken for the circuit in Figure 3 where $C_o = 0.5$ mfd, $C_1 = 0.1$ mfd, $U_o = 850$ v and $\Delta t = 2.5 \cdot 10^{-8}$ sec. Oscillograms of a similar character were obtained for variations in U_i where conditions were the same except that $U_o \geqslant 400$ v. These results show that the path of the $U_i(t)$ curve is independent of the size of the discharging capacitance or of the method of applying voltage — pulse or constant.

In the second series of experiments, the electrodes were sprinkled with metallic powder and the resistance of the resulting bridge was determined. Using the circuit in Figure 3, an oscillogram was taken (Figure 6) for a bridge whose resistance was 1,000 ohms before a pulse was applied. The curve representing $U_i(t)$ with no discharge in the gap is shown dotted on the oscillogram. Comparison with the voltage $U_i(t)$ across the gap when no bridge was present $(R_i > 100,000$ ohms) shows that a reduction in voltage U_i began at point n, approximately $20 \cdot 10^{-8}$ sec before the rapid drop in voltage occurred. (U_i proved to be very stable while it was being recorded by the oscillograph).

This is a most important point because as this change in U_i can only be caused by a bridge with a resistance R of 2-3 ohms, it means that after a period of about $15 \cdot 10^{-8}$ sec from the time a pulse is applied to the gap, the bridge with a resistance $R_i = 1,000$ ohms is able to vary its resistance several hundred times. Consequently, the rapid drop of U_i at point a does not represent a spark-over of the air gap but is instead due to the completion of melting of the bridge which began at point n. At point a the bridge starts to burn and the resistance of the spark gap is rapidly reduced due to ionization of metallic vapors or carbon particles.

Since bridges may be of varied structure and dimensions, their melting and burning will also have a variable character. Thus, the oscillogram in Figure 7, which was taken when the initial resistance of R_i was 4,000 ohms, shows the time of formation of a bridge, with $R_i = 2-3$ ohms, was equal to $35 \cdot 10^{-8}$ sec. The drop in U_i from point a is smoother than that in Figure 6.

A large number of oscillograms taken in similar experiments illustrated the complex nature of the melting of bridges during the consecutive application of a series of pulses to the gap in cases where R_i was more than 100,000 ohms before the circuit was made. The oscillogram in Figure 8 shows two cases; in the first the resistance R_i was more than 100,000 ohms (a gas discharge occurred when U_o equalled 930 v), and in the second burning occurred of a bridge whose resistance R_i was less than 500 ohms prior to the application of voltage. In both cases, consecutive pulses were applied to the gap for 5-10 sec.

It is quite natural that variations in the voltage of U_i occurring during repeated pulse application differ considerably from one another (see Figure 8b where $R_i > 100,000$ ohms in both cases). This variation in the path of the U_i curve indicates a considerable difference in discharges occurring where conditions suitable for the formation of bridges at the electrodes exist (dusty electrodes and small gaps), compared to discharges occurring across clean electrodes with comparatively large interelectrode gaps.

Spark Gap in Contaminated Oil

The following series of experiments was carried out using the circuit shown in Figure 3 under the same conditions as before except that the electrodes were immersed in oil taken from an actual electric-spark cutting machine.

The first experiments were designed to examine the possibility that when bridges are formed, oil surrounding the particles may obstruct their contact. To find out whether bridges form in liquid, the oil container was filled with clean transformer oil. The interelectrode gap was 2.6 mm. At voltages $U_1 = 100$-2,500 v,

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the current in the discharge circuit was less than 1μ a. An emulsion containing a large quantity of metallic dust from a spark-cutting machine was then added drop by drop. As the emulsion was added, the current increased, and when several cubic centimeters had been poured in, it reached 100μ a.

It is of note that when a fine photographic film was interposed between the electrodes ($\delta_e = 0.2 - 0.3$ mm) the flow of current was completely cut off, which indicated a break in the continuity of the bridges. When the contaminated transformer oil was replaced by an emulsion, currents quickly increased with an increase in voltage.

After this, the interelectrode gap was decreased to one mm and the voltage adjusted to 1,270 v. As was expected, the current increased somewhat, due to the increase in gradients. A further increase in voltage made the current flow unstable, and sudden increases in current were observed.

These experiments led to the conclusion that conductive particles in an oil medium can form bridges. In a manner similar to the earlier recordings, these oscillograms showed that a rapid drop in voltage is preceded by a more or less smooth reduction. It also follows that in the case of a gap immersed in oil, bridges are formed extremely quickly. It can be seen from Figure 9 that the curves of $U_1(t)$ vary for three successive discharges occurring at intervals of 5-10 sec. At point a_1, the discharge which began when $U_0 = 330$ v has the appearance of a spark-over, whereas at point a_2 the discharge already has a smoother appearance with $U_0 = 200$ v.

The third discharge is different again, for when $U_1 < 80-90$ v, it deviates noticeably from the initial curve of the pulse voltage. The reduction in U_1 begins at point a_3 when $U_0 = 100$ v and continues smoothly without any rapid drop. It is evident that where a spark gap is working in an emulsion with small interelectrode gaps and $U_0 < 250$ v, discharges are caused by bridges.

A large number of oscillograms of variations in U_1 confirm this conclusion (see Figure 10). Curves 1, 3, 4, and 5, where $U_0 = 80 - 100$ v, illustrate the burning process at the bridges. In curves 2 and 6, where $U_0 = 150$ and 210 v respectively, U_1 drops more sharply, nevertheless, gradual and even sudden increases in voltage are visible, indicating the presence of bridges in the interelectrode gap.

As might be expected, when U_0 is increased the rapid part of the discharge curve becomes steeper and smoother; the role of the bridges is decreased here because the short pulse period makes their formation more difficult. It naturally follows that when the pulse is lengthened, as it is when operating a spark-cutting machine where the discharge time is measured in thousands and tens of thousands of μ sec, conditions for the formation of bridges improve correspondingly.

Investigating the Initial Phase of a Discharge When Operating a Spark-Cutting Machine

After several attempts, a circuit was designed which enabled complete recordings to be made of changes of $U_1(t)$ in the initial phase of a discharge occurring during the normal operation of a spark-cutting machine (Figure 11).

Here, C_0 is the main capacitor of the machine, charging through resistance R_0 and discharging at the spark gap S. The primary winding of a small air-core transformer is connected, through a capacitor, in parallel with gap S, the secondary winding being connected to the electrodes of the spark relay which operates the sweep circuit of the oscillograph. The voltage U_1 under investigation is connected to the deflecting plates of the cathode-ray tube by a 143-m line through which a wave passes in $\tau_c = 71 \cdot 10^{-8}$ sec. Therefore, it is necessary to start the time sweep within this period in order not to miss the beginning of the cycle.

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Control experiments showed that the sweep starts within $30\text{-}40 \cdot 10^{-8}$ sec; consequently, the oscillograph records the first voltage variation of U_1 at the end of the line, magnified twofold, which greatly improves the appearance of the oscillogram. /Text unclear on this point - may be referring to shift in zero axis to coincide with $U_o/2$./ An accurate recording, unbroken by wave reflections, can only be obtained for a period of $143 \cdot 10^{-8}$ sec. The time required for the electron beam to travel across the screen was taken to be $200 \cdot 10^{-8}$ sec.

The oscillograms shown in Figure 12, which were taken using a normally operating spark-cutting machine, where $C = 30\text{-}50$ mfd and $U_o = 300\text{-}350$ v, conform with expected variations of $U_1(t)$ inasmuch as they clearly indicate the melting process of bridges. For comparison purposes, oscillograms were taken of control discharges between clear electrodes in air where voltages of U_o were greater than 400-500 volts, i.e., when the formation of bridges prior to discharge was impossible.

Figure 5a shows a type of recording similar to those obtained from the same circuit in Figure 12, but whereas the voltage drop from U_o to $U_o/2$ took place during the period $\Delta t = (1.9 - 2.6)10^{-8}$ sec in the control oscillograms, the time interval Δt was equal to 22, 7.4, and $9 \cdot 10^{-8}$ sec in the oscillograms shown in Figure 12. Considering that U_o was more than twice as high in the control oscillograms as it was in the oscillogram reproduced in Figure 5a, the change in the relative speed of the drop in U_1 during discharges in an emulsion is even more strikingly emphasized.

Some oscillograms showed an even faster drop in U_1 than those shown, but here the period Δt was several times longer than in the control recordings. However, even in these oscillograms, the relative time for the drop in U_1 from U_o to $U_o/2$ was considerably greater than in oscillograms for discharges in air, which would explain the fact that in these cases the bridges have a fine structure and do not cause very sharp variations of the path of $U_1(t)$ from that obtained in bridgeless discharges.

Spark-over		No of Oscil-logram	U_o in Volts	Interval Δt 10^{-8} sec	$\beta = \dfrac{\Delta t}{U_o}$, 10^{-11} sec	$\beta_{avg} = \left(\dfrac{\Delta t}{U_o}\right)_{avg}$ $.10^{-11}$ sec	$k = \dfrac{\beta}{\beta_{avg}}$
In Air	In Emulsion						
+		1/2	700	2.4	3.43		
+		2/1	730	2.6	3.56	3.33	
+		2/2	590	2.1	3.62		
+		4/2	700	1.9	2.71		
	+	206	300	2.1	7.0		2.1
	+	207	300	2.3	7.65		2.3
	+	208	280	2.3	8.2		2.46
	+	209	310	2.5	8.05		2.42
	+	210	290	2.7	9.3		2.8
	+	211	270	20	74		22.2
	+	212	330	22	67		20.0
	+	213	280	2.3	8.2		2.46
	+	214	280	4.2	15.0		4.5
	+	215	310	22	71.0		21.3
	+	216	250	5.0	20		6.0
	+	217	240	6.0	25		7.5
	+	219	340	2.3	6.8		2.04
	+	220	290	7.4	25.5		7.7
	+	221	310	9.0	29		8.7
	+	222	150	2.3	15.3		4.6

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The above table gives a summary of results obtained from oscillograms and compares them with control recordings. The coefficient β represents the tangent of angle α, subtended by a perpendicular dropped from point n (the beginning of the voltage drop) and a straight line drawn from point n through point m (the intersection f $U_i(t)$ with the time axis) as in Figure 13.

It can be concluded that in the case of a normally operating spark-cutting machine, the initial phase of a discharge conforms with the path of $U_i(t)$ characteristic for the melting process of an interelectrode bridge. It is therefore considered that the contact basis of the discharge has been established.

Measuring Discharge Currents

It was of interest to record current variations in the initial phase of discharge and to establish the effect of bridges on current flow.

To enable oscillograms of current variation $i(t)$ to be taken, a shunt with a dc resistance of 0.5 ohm was connected in series with the spark gap. The character of $U_i(t)$ was, for practical purposes, unaffected by this shunt.

Comparison of current and voltage oscillograms taken in the absence of bridges showed that current first appears at the same time as the spark-over in the air gap begins. Where metallic dust is introduced into the spark gap, current appears when the bridge forms. The size of the current varies from discharge to discharge depending on the value of the contact resistance of the bridge.

Figure 14 shows currents when bridges were present and otherwise. It will be seen that the lower oscillograms are characteristic for a discharge in air, while the top two show the slow increase in current which starts from the moment the bridge is formed.

When the electrodes are short-circuited, the current across them appears at the same time as the beginning of the discharge of capacitor C_1 (Figure 3) in an interval of $3 \cdot 10^{-8}$ sec from the start of the recording, and slowly increases in the same way as it does when conductive bridges are present. In this case the current surge lasts for approximately $70 \cdot 10^{-8}$ sec.

Results

1. The above investigations into the nature of a discharge across an air or oil gap showed that when conditions are favorable for the formation of bridges (either by pyrolysis or erosion products in a liquid medium or by dirty electrode surfaces in air gaps) the beginning of the discharge may be caused by conductive filaments (bridges).

2. When the gap voltage is reduced, which is equivalent to reducing the size of the interelectrode gap, the likelihood of bridges being formed increases, and when the voltage is less than 250-300 v the discharge does not begin with a gaseous spark-over but with the melting or ignition of a conductive bridge. In other words, the discharge begins with an electric contact.

3. The measured time taken to form a bridge amounts to only $(5 - 10) \cdot 10^{-8}$ sec, and during this period the resistance of the bridge drops from thousands of ohms to 2-3 ohms or less. It is evident that these bridges form so quickly that they were not discovered in earlier oscillographic investigations when a relatively slow horizontal sweep was used.

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/See figures on following pages./

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Figure 1.

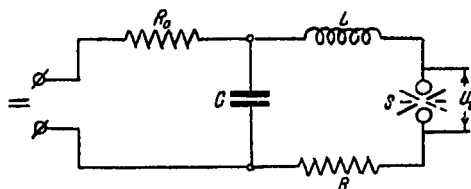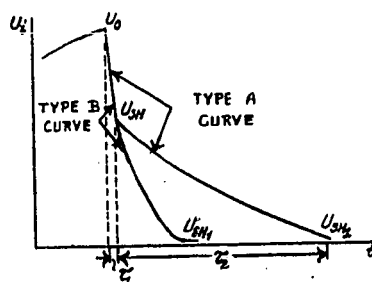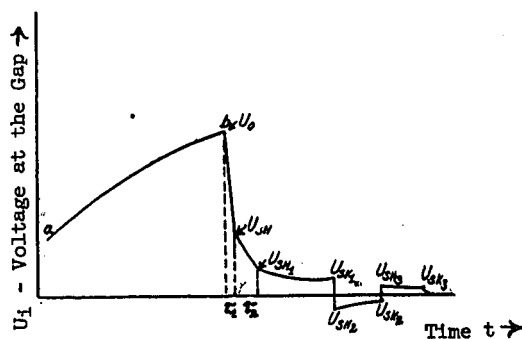Figure 2a. Voltage Variation Curve of U_1 at the Spark Gap
During a Discharge in Air

Figure 2b. Graph of the Function $U_1 = f(t)$

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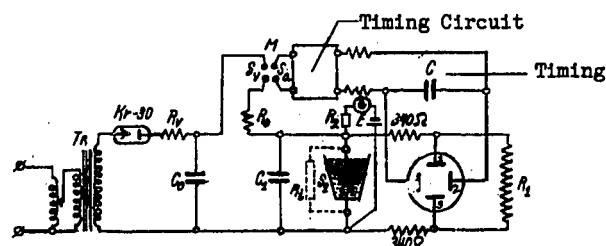
Figur. 3.   Circuit for Taking Oscillograms of Initial Phase of Discharge
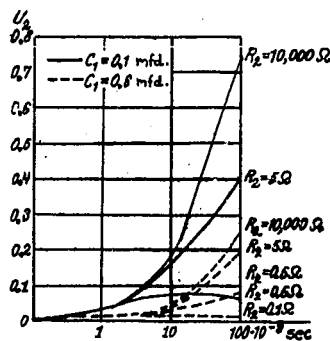
Figure 4.
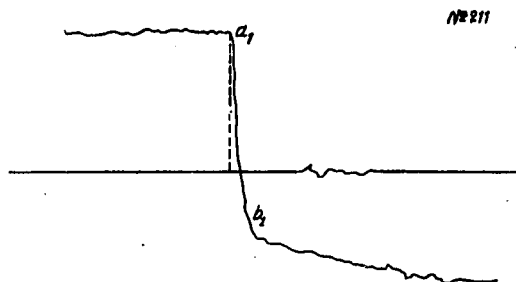
Figure 5a.

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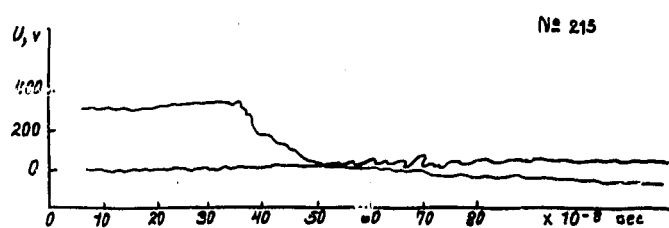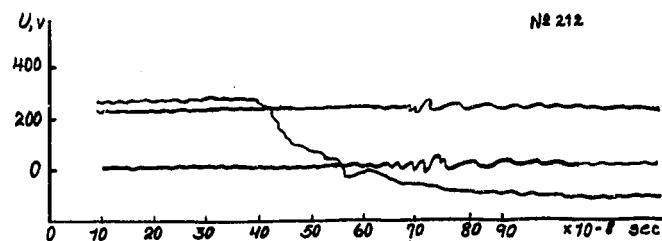
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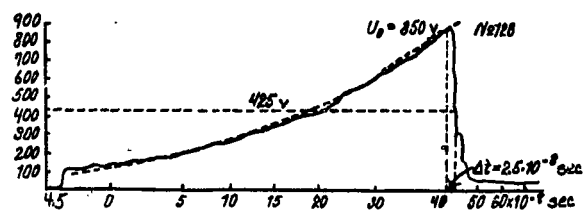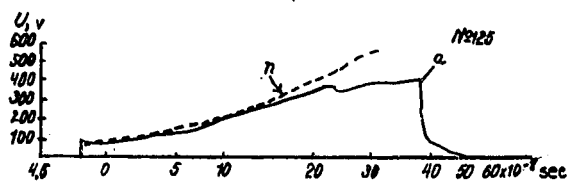
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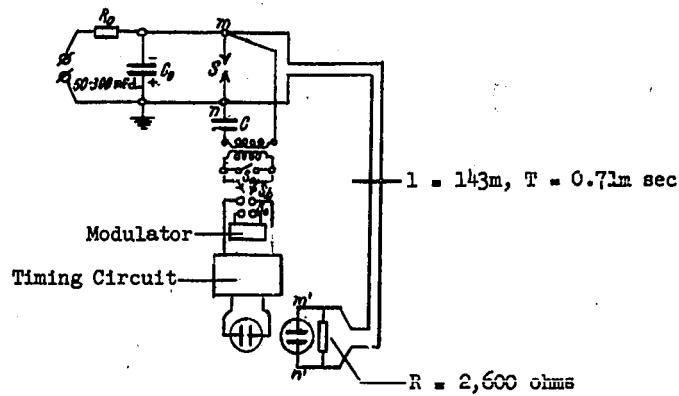
Figure 5b.

Figure 6.
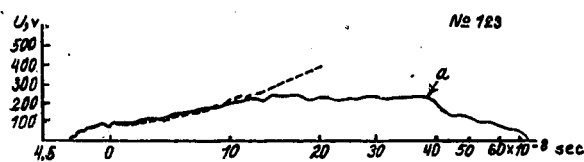
Figure 7.

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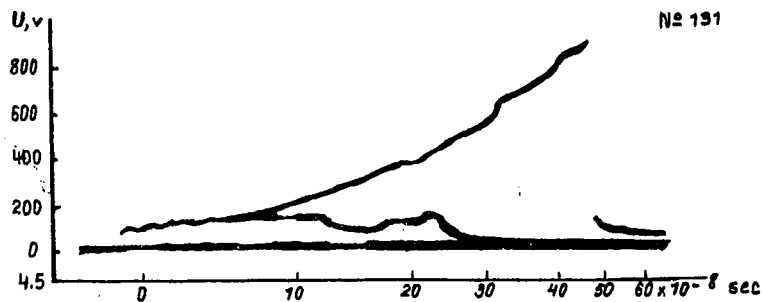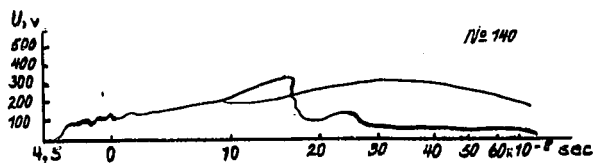
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Figure 8a.

Figure 8b.
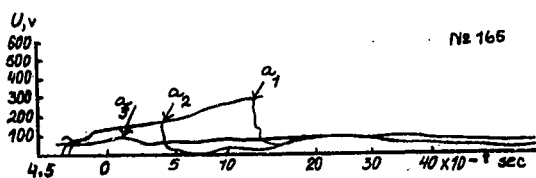
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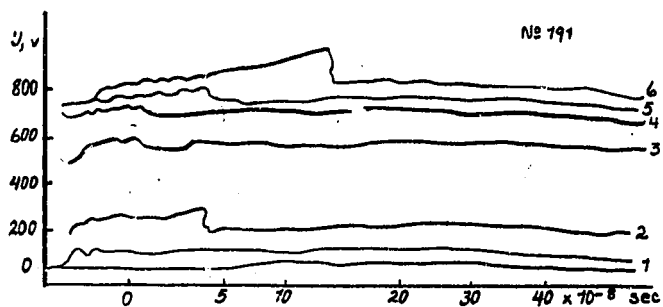
Figure 10.

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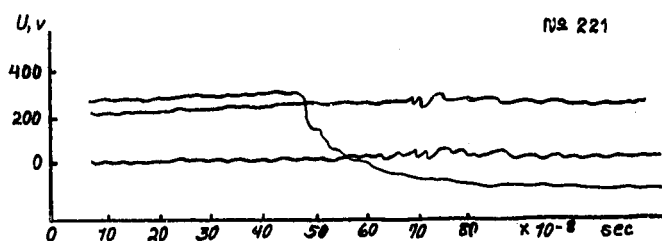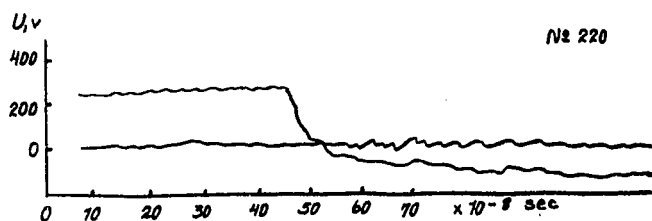
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Figure 12

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$1 = 143m, T = 0.71m sec$

$R = 2,600 ohms$

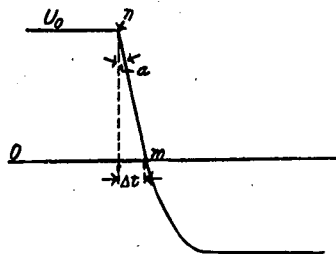Figure 11. Timing Circuit for Recording the Initial Phase of a Pulse, Using a Normally Operating Spark-Cutting Machine

Figure 13.

Figure 14.
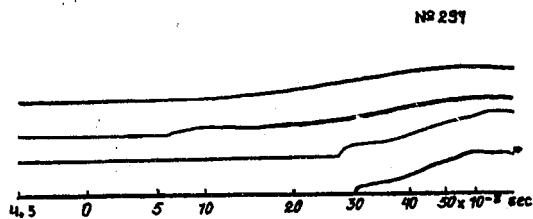
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